ARO 24706.4-GS

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AD-A212 226

Radar Polarimetric Studies Based on the MAYPOLE
1983 & 1984 Field Experiments

Final Technical Report

Kultegin Aydin and Thomas A. Seliga

August 10, 1989

U. S. Army Research Office

Contract Number: DAAL03-87-K-0031

The Pennsylvania State University

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
ARO 24706.4-GS

6a. NAME OF PERFORMING ORGANIZATION
Pennsylvania State Univ.

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION
U. S. Army Research Office

6c. ADDRESS *(City, State, and ZIP Code)*
University Park, PA 26802

7b. ADDRESS *(City, State, and ZIP Code)*
P. O. Box 12211
Research Triangle Park, NC 27709-2211

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
U. S. Army Research Office

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
DAAL03-87-K-0031

8c. ADDRESS *(City, State, and ZIP Code)*
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO

11. TITLE *(Include Security Classification)*
Radar Polarimetric Studies Based on the MAYPOLE 1983 & 1984 Field Experiments

12. PERSONAL AUTHOR(S)
Kultegin Aydin and Thomas A. Seliga

13a. TYPE OF REPORT
Final

13b. TIME COVERED
FROM 3/15/87 TO 6/14/89

14. DATE OF REPORT *(Year, Month, Day)*
August 10, 1989

15. PAGE COUNT
15

16. SUPPLEMENTARY NOTATION
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Radar Polarimetric Studies, Rainfall Rates, Hail, Storms

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This research was conducted for the purpose of evaluating and improving the interpretation of multiparameter radar measurements (dual-linear polarization and dual wavelength) in rainfall and hail. The specific aspects of this research involved case studies from MAYPOLE comparing estimates of rainfall rate obtained from radar and ground based

(over)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE *(Include Area Code)*

22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

raingauge measurements and the development of analysis techniques for this purpose. Understanding and interpreting multiparameter radar measurements in hail was another problem which required analyzing radar data within the hail regions of a storm identified using the differential reflectivity hail signal. Computational radar scattering studies were also conducted for this purpose. Finally, correction for propagation effects in rainfall (mainly attenuation) on radar signals at C-band frequencies was another problem that was considered. A summary of the main results are presented in this report.

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FOREWORD

As a result of a cooperative research program involving the principal investigators and researchers from Colorado State University, and NCAR's Field Observing Facility (FOF), the CP-2 radar system was modified during 1982-83 to include co-polar dual linear polarization measurements at S-band in addition to Doppler velocity and dual wavelength reflectivity measurements. An X-band linear depolarization ratio measurement capability was also added in 1984. These modifications resulted in a very successful series of experiments conducted in May-June of 1983 and 1984 under the acronym MAYPOLE (MAy POLarization Experiments). Project MAYPOLE was designed to assess the utility of multiparameter radar measurements for hydrometeor detection and classification, quantitative rainfall characterization, and for extrapolation of aircraft sampling of hydrometeors to entire cloud systems. The research supported by this contract focused on analyzing radar and ground based in situ observations of selected rainfall and hail events obtained during MAYPOLE, together with computational and theoretical studies of radar scattering from hydrometeors for improving the interpretation of the radar measurements.

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1. STATEMENT OF THE PROBLEM STUDIED

This research was conducted for the purpose of evaluating and improving the interpretation of multiparameter radar measurements (dual-linear polarization and dual wavelength) in rainfall and hail. The specific aspects of this research involved case studies from MAYPOLE comparing estimates of rainfall rate obtained from radar and ground based raingauge measurements and the development of analysis techniques for this purpose. Understanding and interpreting multiparameter radar measurements in hail was another problem which required analyzing radar data within the hail regions of a storm identified using the differential reflectivity hail signal. Computational radar scattering studies were also conducted for this purpose. Finally, correction for propagation effects in rainfall (mainly attenuation) on radar signals at C-band frequencies was another problem that was considered. A summary of the main results are presented in the following section. More detail can be found in the references which are listed in Section 3.

2. SUMMARY OF THE MOST IMPORTANT RESULTS

The results of this research will be summarized under two main categories. These are: (1) rainfall and related studies, and (2) hailfall studies.

2.1 Rainfall and Related Studies

2.1.1 Comparison of Radar and Raingauge/Disdrometer Measurements

A case study was conducted using data collected in rainfall on June 16, 1984 during MAYPOLE'84. Estimates of rainfall rate obtained with the differential reflectivity (Z_{DR}) technique and two Z-R relations

(Marshall-Palmer and Jones' thunderstorm) were compared with measurements from two PAM (Portable Automated Mesonet) station raingauges located in different parts of the storm. The comparisons were made systematically, taking into account the speed and direction of the storm's motion. The temporal averaging performed on the raingauge data was matched with the spatial averaging of the radar measurements. The differential reflectivity radar estimates of rainfall rate compared very favorably with those obtained from the PAM measurements. The biases were +13% (overestimated by radar) and +1% and the standard errors were 38% and 22% for PAM station 1 and 2, respectively. The Marshall-Palmer (MP) and Jones' Thunderstorm (J) Z-R relationships were also evaluated. For PAM station 1, the MP relationship produced -13% bias (underestimated by radar) and 39% standard error, and Jones' relationship produced -21% bias and 38% the standard error. For PAM station 2, the MP relationship produced -25% bias and 28% standard error, and Jones' relationship produced -38% bias and 34% standard error. It is seen that MP and J compare reasonably well with PAM1 and not so well with PAM2, whereas the Z_{DR} technique did well in both comparisons. These results were presented at IGARSS'89 (Aydin et al., 1989c) and will be submitted for publication in IEEE Transactions Geoscience and Remote Sensing in September 1989.

A study which was initiated earlier on radar-disdrometer comparisons was finalized and published (Aydin et al., 1987a,b). In this study rainfall parameters estimated from dual-polarization radar measurements using the differential-reflectivity technique were compared with ground-based disdrometer measurements located 47.1 km from the radar. Data obtained with the dual polarization CHILL radar during an experiment in central Illinois on October 29, 1982 were utilized. Both empirical and model relationships between radar observables and rainfall parameters were tested. The differential-reflectivity technique was compared with the conventional Z-R technique and shown to provide improvements in the estimation of rainfall rate. The analysis included careful consideration of the spatial and temporal factors relating the radar-scattering volumes to the location and duration of ground-based disdrometer measurements. The significance of these factors (mainly due to the horizontal and vertical motion of raindrops) in radar-disdrometer comparisons was evident in the results. The Z_{DR} technique produced +9% bias (overestimated by radar) and 24% standard error, whereas the Marshall-Palmer Z-R relationship produced +99% bias and 65% standard error.

2.1.2 C-band Radars: Rainfall Measurements and Propagation Effects

The utilization of C-band radars is of growing interest due to the smaller antenna size requirements and costs compared to S-band radars having the same beamwidths. Therefore, empirical relationships between dual-linear polarization radar observables (reflectivity factor Z_H and differential reflectivity Z_{DR}) and rainfall parameters (rainfall rate R, water content M, and median volume raindrop diameter D_0) were generated based on disdrometer measurements of raindrop size distributions (Aydin et al., 1988b). These relationships should be useful in estimating R, M and D_0 with dual polarization C-band radars. Statistical error analyses indicate that R (or M) - (Z_H, Z_{DR}) formulas yield considerably smaller errors than values obtained from R (or M) - Z relationships.

At C-band wavelengths the reflectivity factor and differential reflectivity are affected by the attenuation of radiowaves due to rainfall. An attenuation correction procedure for C-band dual linear polarization radars was introduced and evaluated using disdrometer-based simulations (Aydin et al., 1987c, 1989a). It was shown that retrieving C-band reflectivity factors and differential reflectivities is possible under certain conditions. The procedure was very sensitive to biases (which include calibration errors) in the measurements of Z_H and Z_{DR}. The simulated rainfall paths considered here indicated that biases in Z_H and Z_{DR} measurements should be within ±1 and ±0.2 dB, respectively. The study focused on simulated raincells with rainfall rates limited to five selected categories within the range 2-150 mm h^{-1}. Furthermore, a raincell along a 29-km path with rainfall rates varying from 0.5 to 88 mm h^{-1} was simulated in order to demonstrate the correction procedure over an extended path with large rainfall rate gradients. The results show that the correction procedure reduces the errors (created by attenuation due to rain) in the measured values of Z_H and Z_{DR}, thus leading to improved overall estimates of rainfall rate.

Another study related to C-band attenuation was conducted in order to demonstrate that S-band dual polarization measurements are an effective means of predicting the reflectivity and attenuation behavior of C-band electromagnetic waves in rainfall (Direskeneli et al., 1987). During the MAYPOLE field program in Colorado in 1984, there was an opportunity for the National Center for Atmospheric Research's CP-2 (S-band dual linear polarization) and CP-4 (C-band) radars to simultaneously operate and observe a storm system from different locations 28 km apart. The measurements obtained from this experiment made it possible to test the prediction procedure mentioned above. A raincell which had reflectivities greater than 50 dBZ was considered as a case study. Using the S-band dual polarization measurements, the C-band 'apparent' reflectivity profiles were predicted and compared with the measurements of the C-band radar. The comparisons were very good showing a mean error less than 2.2 dB in reflectivity factors ranging from 30 to 55 dBz.

2.1.3 Dual-Polarization Radar Estimation of Aerosol Scavenging by Rainfall

Since the differential reflectivity (Z_{DR}) method has been proven successful for estimating rainfall rate and drop size with good accuracies (e.g., Aydin et al., 1987a), it is also an excellent candidate for estimating aerosol scavenging in addition to other rainfall-dependent phenomena. For this purpose, the dependence of the scavenging rate, Λ on raindrop size distribution N(D) was shown. Assuming (Z_H, Z_{DR}), where Z_H is the reflectivity factor at horizontal polarization, are sufficient to describe N(D), an empirical method of relating these radar observables to Λ was proposed (Seliga et al., 1989). The disdrometer-based simulations of scavenging rate time histories for different aerosol radii and raindrop size categories demonstrated that the two-parameter (Z_H, Z_{DR}) method of estimating Λ produced very good agreement with actual values. This suggests that (Z_H, Z_{DR}) measurement of Λ may prove useful for remote estimation of aerosol scavenging rates, similar to their use for estimating R and the microwave specific attenuation. This result derives from the fact that Z_{DR} helps account for the variability in the raindrop size distribution.

2.1.4 Discrimination of Rainfall and Clutter

The presence of undetected mixed-phase precipitation or superimposed intense clutter can cause serious errors in the estimation of rainfall-rate and other parameters of precipitation occurring in the scattering volume.

To reduce or avoid these errors it is necessary to distinguish between the rain-echo and that due to other types of precipitation and between precipitation radar-echoes and ground clutter. In this study multiple parameter radar classification schemes were used for discrimination of rainfall from ground clutter (Freni et al., 1988, 1989). Single or combined tests on dual polarization radar observables (Z_H, Z_{DR}), Doppler velocity and area clutter maps were utilized for this purpose. The classification schemes relied heavily on the rainfall discrimination capability of Z_H and Z_{DR}, The spatial variability of Z_{DR} appeared promising for ground clutter vs. rain discrimination. Preliminary studies, using actual radar measurements from MAYPOLE, produced very encouraging results. The assessment of the proposed schemes requires considerably more research focusing on different rainfall conditions. Potential applications include real time processing of radar data for estimating spatial distributions of rainfall rates for weather and hydrological nowcasting purposes.

2.1.5 Effects of Reflectivity Gradients on the Estimation of Rainfall

It has been shown that the reflectivity gradients within the radar measurement cell can significantly bias the reflectivity measurements. This bias or error depends also on the receiver transfer function and on the number of the averaged samples. In this study the effects on an exponential spatial variation in the parameters (N_O, D_O) of an exponential drop size distribution on the radar observables (Z_H, Z_{DR}) and derived rainfall rates were examined (Scarchilli et al., 1988, 1989). The bias of the estimates, their fractional standard deviations and the optimum receiver response were computed for radar observations with a stationary antenna. The results indicated a strong dependence on receiver type and signal processing. Computations suggested that, for rainfall rate estimation from the radar observables, excellent results can be obtained with a square law receiver. In order to reduce the error in the rainfall estimates in the presence of reflectivity gradients, related studies are in progress for retriving the parameters which characterize the spatial variation of the exponential drop size distribution parameters. (N_0 and D_0).

2.2 Hailfall Studies

2.3.1 Multiparameter Radar Observations of Hailstorms

Multiparamter-polarimetric radars are increasingly being used for studying the microphysics of convective storms (see e.g., the American Meteorological Society's Preprints of the 24th Conference on Radar Meteorology, 1989). Techniques for collecting, processing and interpretating radar measurements are being developed for this purpose. Improved understanding of hailstorm processes is possible with the aid of such radar techniques. In this study, multiparameter radar measurements obtained in MAYPOLE during the 13 June 1984 Denver hailstorm were used to demonstrate a differential reflectivity technique for observing hailstorms (Aydin et al., 1988a, 1989b, 1989d). The hail regions of the storm were identified using H_{DR} (i.e., a differential reflectivity hail signal). Histograms of Z_H and Z_{DR} at different heights and the vertical profiles of their mean values were generated. The relative variation of these parameters in the hail regions was also determined. A significant feature was the increase in the mean values of Z_H and Z_{DR} with decreasing height which was attributed to the melting of the hailstones. At the lower elevations, it was also observed that Z_{DR} varied between -1 and +2 dB and Z_H was generally greater than 50 dBZ. $\bar{Z}_H$ reached a peak value (60 dBZ or more) when Z_{DR} was in the range -0.5 to 0 dB and 1.5 to 2 dB at 1.5 km and 2 km below the $0^{o}C$ level, respectively. These and other features of the radar observables (including dual wavelength ratio DWR and linear depolarization ratio LDR) were interpreted in terms of the size, shape and fall behavior of the hailstones with input from electromagnetic scattering computations using model hailstones. For example, the negative Z_{DR} regions in this storm were inferred to be most likely composed of melting hailstones with sizes predominately in the range 12 to 40 mm, which fall with their larger dimension aligned (on the average) vertically. On the other hand, positive Z_{DR} values greater than 1 dB were concluded to be due to melting hailstones with sizes less than 12 mm, which fall with their larger dimensions aligned (on the average) horizontally. These and other results indicate that multiparameter radar measurements (in this case Z_H, Z_{DR}, DWR and LDR) together with scattering computations can provide significant qualitative and quantitative information about the hail medium.

In another study based on multiparameter radar measurements obtained during MAYPOLE'84, three hail detection techniques were comparatively studied (Aydin et al., 1988c). These were the differential reflectivity technique, the dual wavelength technique and the reflectivity threshold technique. The results indicate a general agreement among the three techniques due to the existence of regions where all three predict hail. However, there are significant differences in the extent and the location of the hail regions. A manuscript presenting these findings is being prepared for a journal publication.

2.2.2 A Computational Study of Polarimetric Radar Observables in Hail

Remote measurement of hail parameters remains a challenging problem in radar meteorology due to the complex shape, composition and falling behavior of melting hailstones. Dual polarization radars have been successfully used in improving rainfall parameter estimation (Aydin et al., 1987a), and mapping hail regions within storms (Aydin et al., 1989d). Polarimetric radars are also expected to be useful in estimating hail parameters such as size distribution, hailfall rate, median size, kinetic energy, liquid water content, etc. In order to obtain meaningful relationships between polarimetric radar observables and hail parameters, it is essential to utilize a melting model for hailstones. A computational study based on such a model was initiated and preliminary results were reported at IGARSS'89 (Aydin and Zhao, 1989). The melting model provides the vertical profiles of size, shape and water coating on hailstones given their size at the $0^{o}C$ level (assuming spherical or oblate spheroidal shapes) together with the environmental temperature and humidity profiles. Electromagnetic scattering computations were performed at a wavelength of 10.7 cm for water-coated oblate spheroidal ice particles corresponding to different heights below the $0^{o}C$ level. At the 0^{o} level all of the ice particles were assumed to have axial ratios of 0.9 the minor axis (i.e., the symmetry axis) of each hailstone to be vertically aligned. Preliminary results for monodisperse size distributions indicate that there are significant changes in the radar observables (reflectivity factor Z_H, differential reflectivity Z_{DR}, specific differential phase shift K_{DP}, and circular depolarization ratio CDR). The melting process increases the water coating on the hailstones and enhances the oblateness (i.e., decreases the axial ratio). For hailstones with diameters less than 30 mm, Z_H, Z_{DR}, and CDR tend to increase with increased melting. Beyond 40 mm Z_{DR} changes sign and CDR increases rapidly reaching a peak value of 20 dB at D = 55 mm. Oscillations in K_{DP} with size increases significantly as the hailstones melt. The computations will be extended to exponential size distributions which are more commonly observed. The results will be published in IEEE Transactions on Geoscience and Remote Sensing.

3. LIST OF PUBLICATIONS

3.1 Journal Publications

Aydin, K., H. Direskeneli, and T. A. Seliga, "Dual Polarization Radar Estimation of Rainfall Parameters Compared with Ground-Based Disdrometer Measurements: 29 October 1982, Central Illinois Experiment," IEEE Trans. Geosci. Remote Sensing, 25, 834-844, 1987.

Aydin, K., Y. Zhao, and T. A. Seliga, "Rain-Induced Attenuation Effects on C-Band Dual Polarization Meteorological Radars," IEEE Trans. Geosci. Remote Sensing, 27(1), 57-66, 1989.

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3.2 Conference Publications

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Aydin, K., Y. M. Lure and T.A. Seliga, "Bistatic Polarimetric Scattering for Remote Estimation of Droplet Size Distribution in Clouds and Fog," Preprints, 24th Conference on Radar Meteorology, Tallahassee, Florida, AMS, 283-286, 1989.

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3.3 Ph.D. Theses

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4. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND ADVANCED DEGREES AWARDED DURING

This project was jointly supervised by Thomas A. Seliga (CO-PI), Professor of Electrical Engineering and Associate Dean for Graduate Studies and Research and Dr. Kultegin Aydin (CO-PI), Assistant Professor of Electrical Engineering.

Three doctoral students were supported by this project, Haldun

Direskeneli, Yang Zhao, and Y. M. Lure. Haldun Direskeneli was awarded a Ph.D. degree in the summer of 1987, in Electrical Engineering at The Ohio State University. Yang Zhao will be defending his thesis in August 1989 and should officially be awarded a Ph.D. degree in Electrical Engineering at Penn State in December 1989. Y. M. Lure is continuing his Ph.D. thesis work and is expected to graduate in December 1989.

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